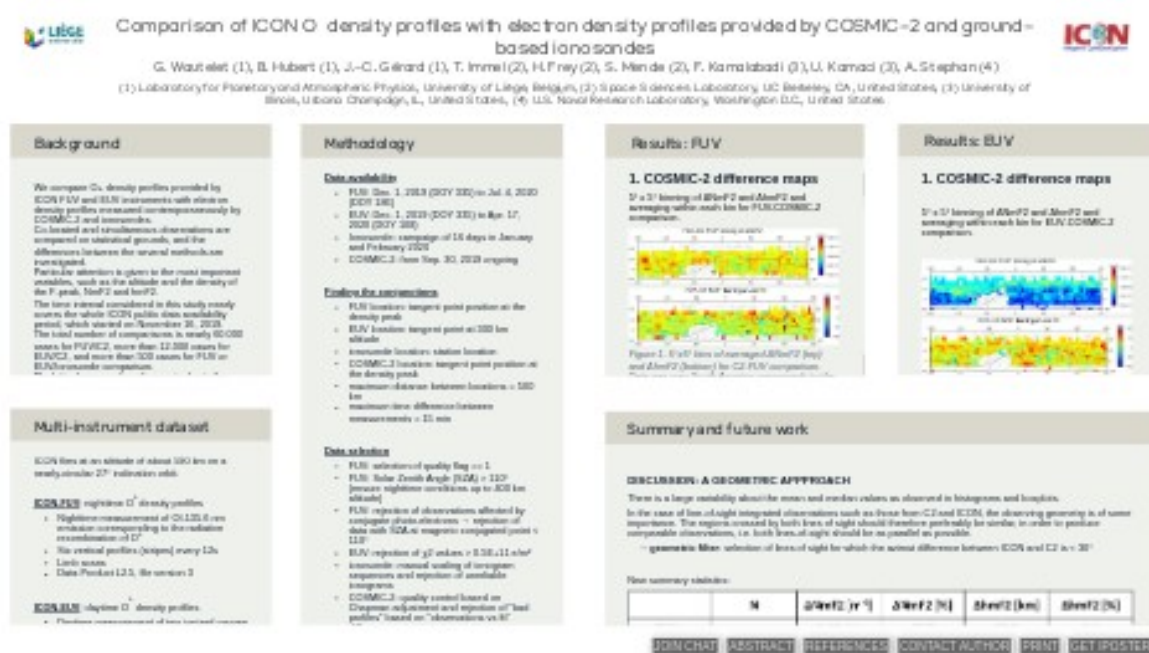


Comparison of ICON O⁺ density profiles with electron density profiles provided by COSMIC-2 and ground-based ionosondes



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PRESENTED AT:



BACKGROUND

We compare O⁺ density profiles provided by ICON FUV and EUV instruments with electron density profiles measured contemporaneously by COSMIC-2 and ionosondes.

Co-located and simultaneous observations are compared on statistical grounds, and the differences between the several methods are investigated.

Particular attention is given to the most important variables, such as the altitude and the density of the F-peak, NmF2 and hmF2.

The time interval considered in this study nearly covers the whole ICON public data availability period, which started on November 16, 2019.

The total number of comparisons is nearly 60.000 cases for FUV/C2, more than 12.000 cases for EUV/C2, and more than 500 cases for FUV or EUV/ionosonde comparison.

The latter lower number of cases is due to the necessary manual screening and scaling of ionogram sequences to ensure reliable ionosonde profiles, while COSMIC-2 data are carefully selected using an automatic quality control algorithm.

MULTI-INSTRUMENT DATASET

ICON flies at an altitude of about 590 km on a nearly-circular 27° inclination orbit.

ICON-FUV: nighttime O⁺ density profiles

- Nighttime measurement of OI-135.6 nm emission corresponding to the radiative recombination of O⁺
- Six vertical profiles (stripes) every 12s
- Limb scans
- Data Product L2.5, file version 3

ICON-EUV: daytime O⁺ density profiles

- Daytime measurement of two ionized oxygen emissions at 83.4 and 61.7 nm
- One vertical profile every 12s
- Limb scans
- Data Product L2.6, file version 2

Ionosonde: electron density profiles

- Vertical incidence soundings performed in radio frequencies between 1 and 30 MHz
- Direct measurement of the plasma frequency fof2. An inversion is needed to retrieve the true reflection height hmF2
- 14 fixed ground stations, mainly in the northern hemisphere at mid-latitudes, have been used in this study. Only one station is located in the low-latitude ionosphere. This observational bias has to be taken into account when discussing ionosonde results
- Each ionogram sequence is manually scaled by the authors thanks to the SAO-X software developed by University of Massachusetts, Lowell.

COSMIC-2 (C2): electron density profiles

- Radio occultation of GNSS satellites using GNSS receivers onboard Low-Earth Orbit (LEO) spacecraft
- The six LEO satellites are on low-inclination orbit so that C2 profiles also observe low and mid latitudes
- GNSS-TEC (Total Electron Content) is an integrated quantity that has to be inverted to get the electron density profile
- C2 mission was launched in 2019 and provides more than 3.000 ionospheric profiles per day
- "IonPrf" product (provisional space-weather dataset)

METHODOLOGY

Data availability

- FUV: Dec. 1, 2019 (DOY 335) to Jul. 4, 2020 (DOY 186)
- EUV: Dec. 1, 2019 (DOY 335) to Apr. 17, 2020 (DOY 108)
- Ionosonde: campaign of 16 days in January and February 2020
- COSMIC-2: from Sep. 30, 2019 ongoing

Finding the conjunctions

- FUV location: tangent point position at the density peak
- EUV location: tangent point at 300 km altitude
- ionosonde location: station location
- COSMIC-2 location: tangent point position at the density peak
- maximum distance between locations = 500 km
- maximum time difference between measurements = 15 min

Data selection

- FUV: selection of quality flag == 1
- FUV: Solar Zenith Angle (SZA) > 110° (ensure nighttime conditions up to 400 km altitude)
- FUV: rejection of observations affected by conjugate photo-electrons → rejection of data with SZA at magneto conjugated point < 110°
- EUV: rejection of χ^2 values > 0.5E+11 e/m²
- ionosonde: manual scaling of ionogram sequences and rejection of unreliable ionograms
- COSMIC-2: quality control based on Chapman adjustment and rejection of "bad profiles" based on "observations vs fit" differences
- COSMIC-2: smear < 2200 km (correspond to an average ICON smear)

RESULTS: FUV

1. COSMIC-2 difference maps

5° x 5° binning of $\Delta N m F_2$ and $\Delta h m F_2$ and averaging within each bin for FUV-COSMIC-2 comparison.

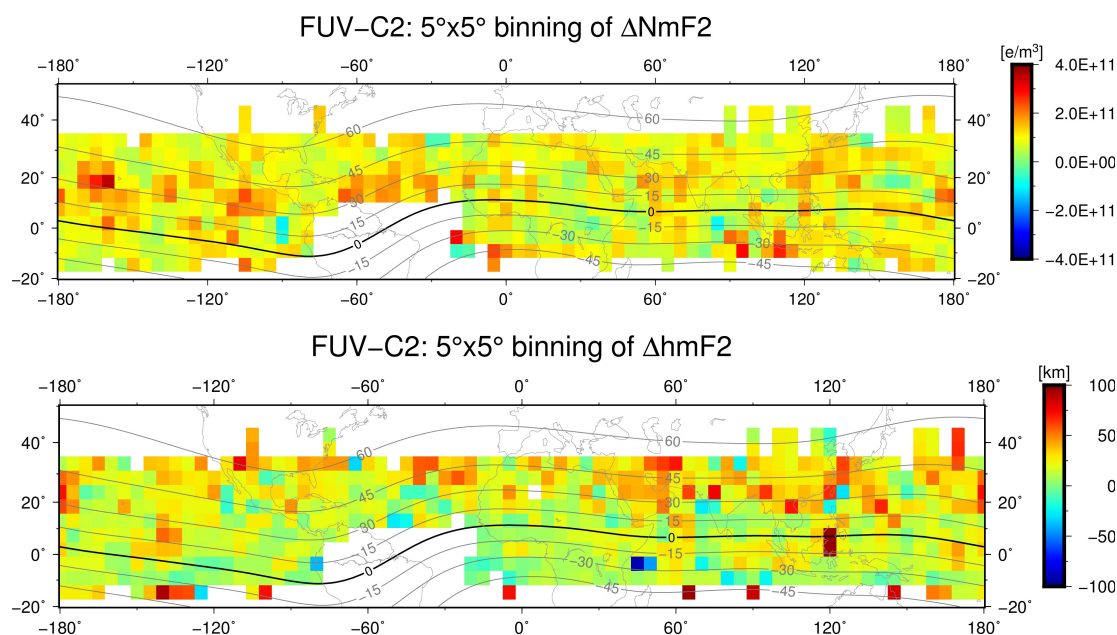


Figure 1. 5°x5° bins of averaged $\Delta N m F_2$ (top) and $\Delta h m F_2$ (bottom) for C2-FUV comparison. Data gap over South America corresponds to the South Atlantic Anomaly (SAA). Contour lines correspond to geomagnetic inclination, in degrees.

Analysis

- $\Delta N m F_2$ and $\Delta h m F_2$ are mostly positive at all locations
- $\Delta N m F_2$ are mostly homogeneously distributed on the map, despite the existence of some clusters (e.g. Caribbean, Hawaii and East Pacific sectors) which should be further investigated
- $\Delta h m F_2$ are larger at mid-latitudes, especially in the northern hemisphere

2. Summary statistics

	N	$\Delta N m F_2$ [m^{-3}]	$\Delta N m F_2$ [%]	$\Delta h m F_2$ [km]	$\Delta h m F_2$ [%]
FUV - COSMIC-2	59997	9.64E+10 +/- 1.10E+11	55.1 +/- 104.5	15.5 +/- 31.4	5.9 +/- 11.6
FUV - ionosonde	563	9.65E+10 +/- 5.10E+10	71.6 +/- 60.0	37.6 +/- 35.4	14.1 +/- 13.3

Table 1. Mean and standard deviation of $\Delta N m F_2$ and $\Delta h m F_2$ for FUV-C2 and FUV-ionosonde comparisons

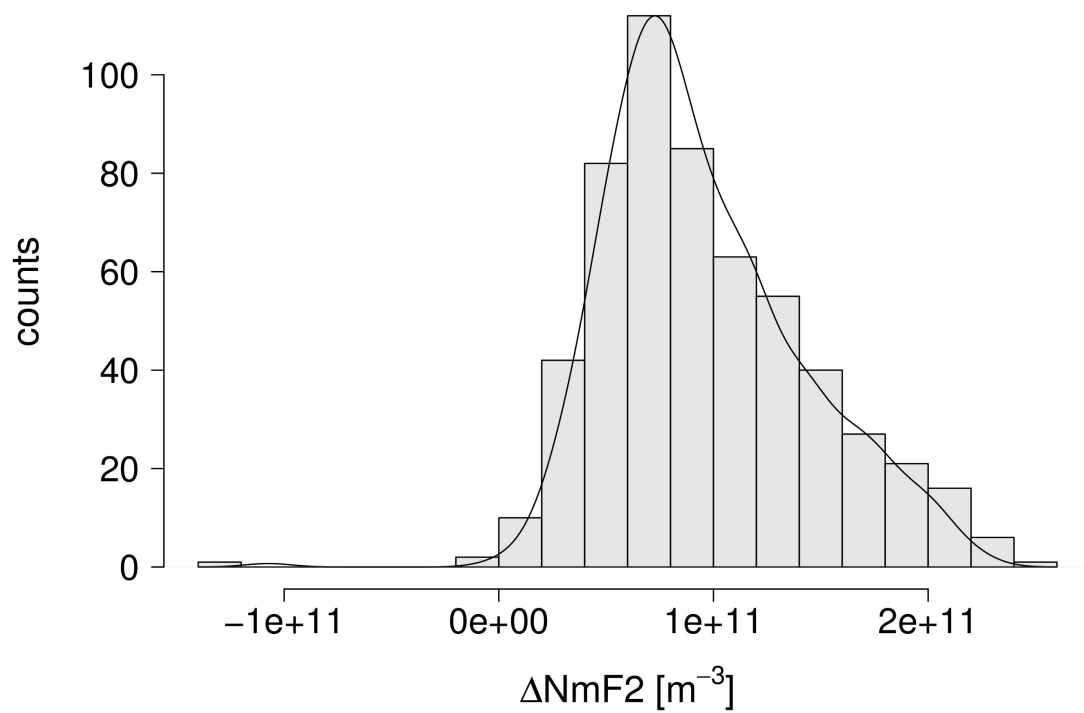


Figure 2a. Histogram of $\Delta NmF2$ for FUV-ionosonde comparison

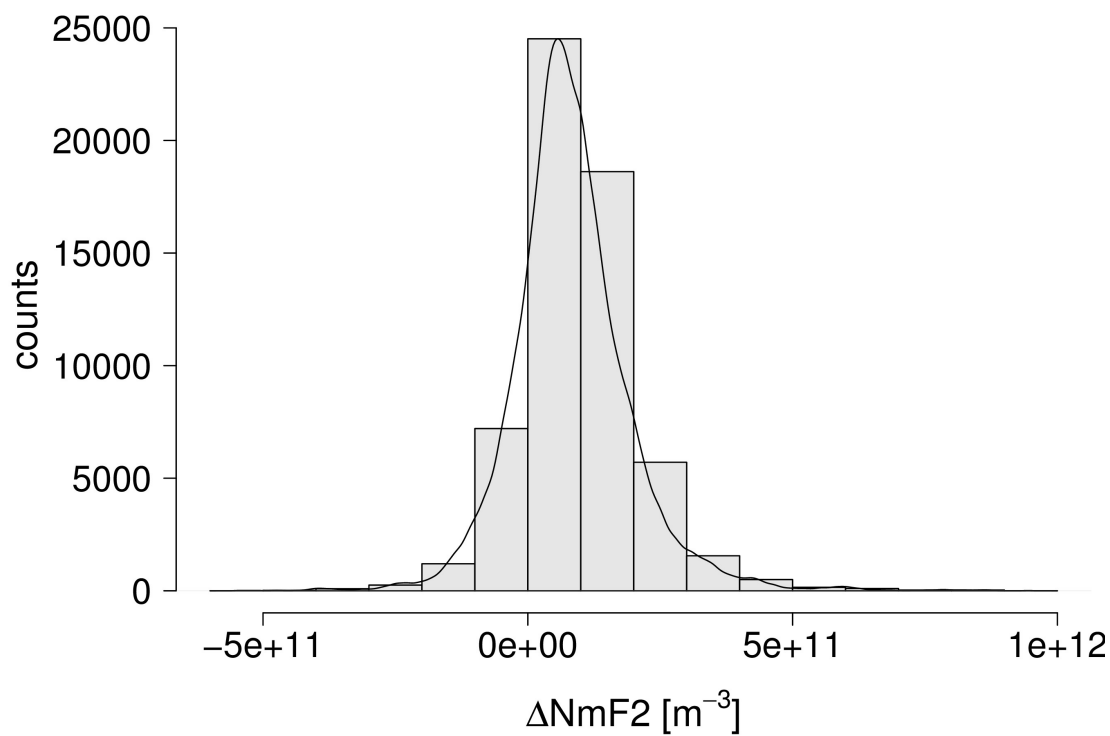


Figure 2b. Histogram of $\Delta NmF2$ for FUV-C2 comparison

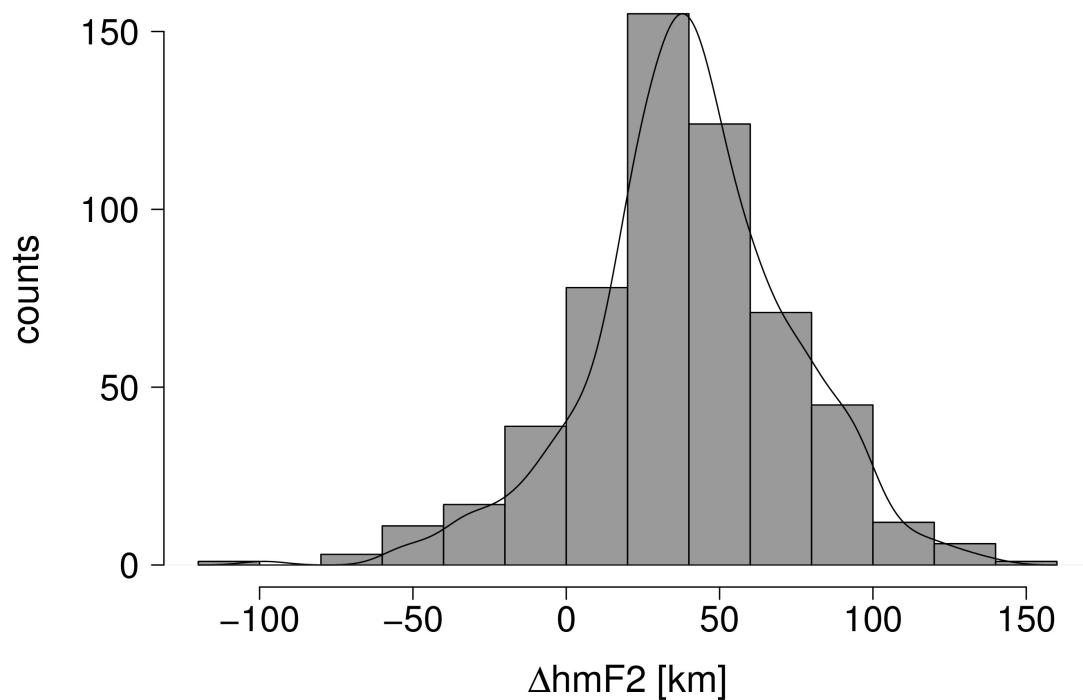


Figure 2c. Histogram of $\Delta hmF2$ for FUV-ionosonde comparison

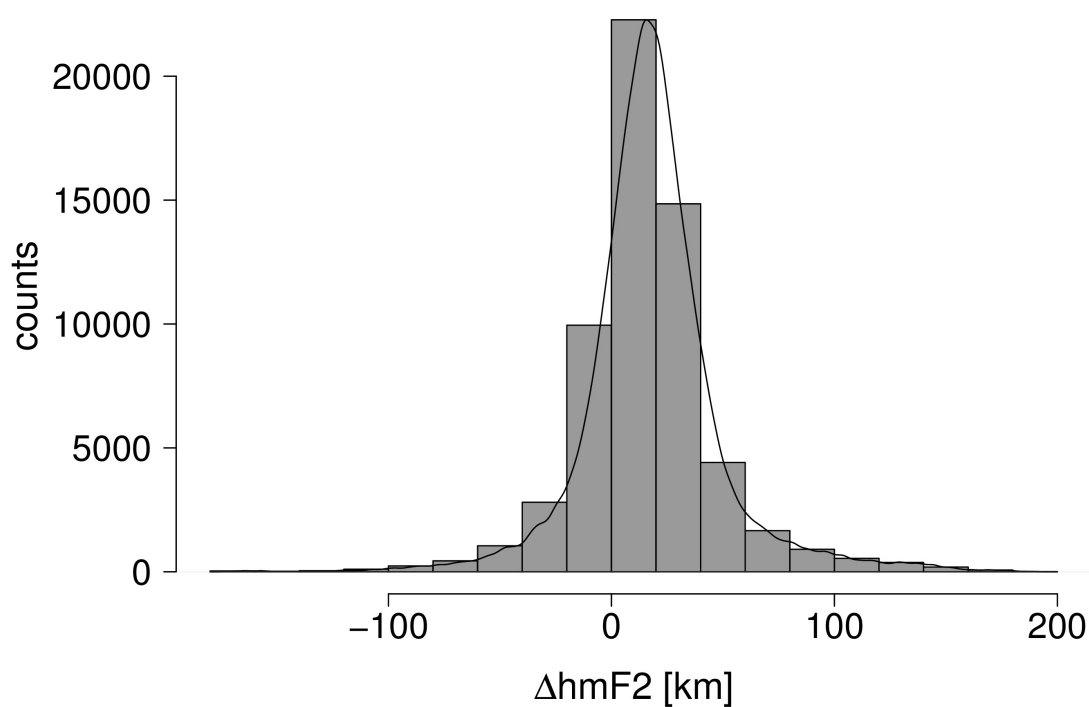


Figure 2d. Histogram of $\Delta hmF2$ for FUV-C2 comparison

Analysis

- Except for Figure 2a, the quasi-Gaussian shape of the histograms validate the descriptive statistics in Table 1 (mean and std. dev.)
- Ionosonde and COSMIC-2 analyses lead to similar conclusions for NmF2, while there are some differences in

absolute values for $\Delta h m F_2$

- FUV NmF2 is slightly larger than that of C2 and ionosonde, with a mean value of $9.6E+10 \text{ e/m}^3$
- FUV hmF2 is larger than that of C2 and ionosonde, with mean values of 15 km and 38 km respectively
- Relative differences for NmF2 are explained by a very low background ionosphere due to solar minimum conditions.

3. SLT dependence

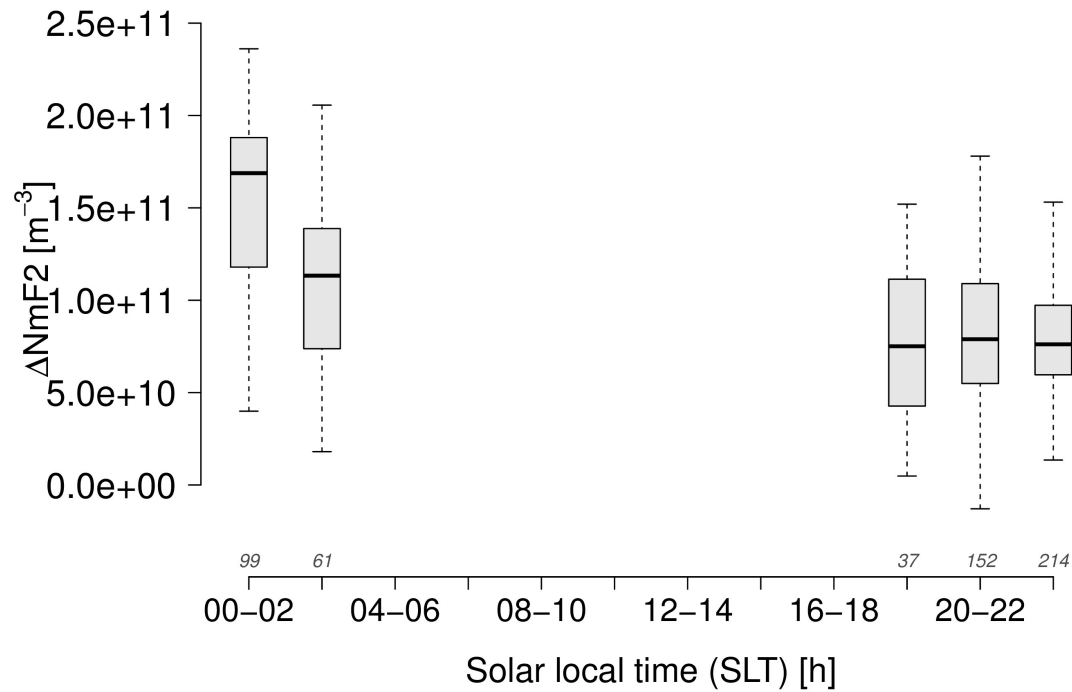


Figure 3a. Boxplots of $\Delta N m F_2$ for FUV-ionosonde comparison for six SLT intervals. Boxes represent the quartiles, the median is the thick black line inside the box while the whiskers are located at 1.5 times the interquartile range. The small numbers in italic below the boxplots correspond to the sample size. Outliers are removed from the panel for the sake of clarity.

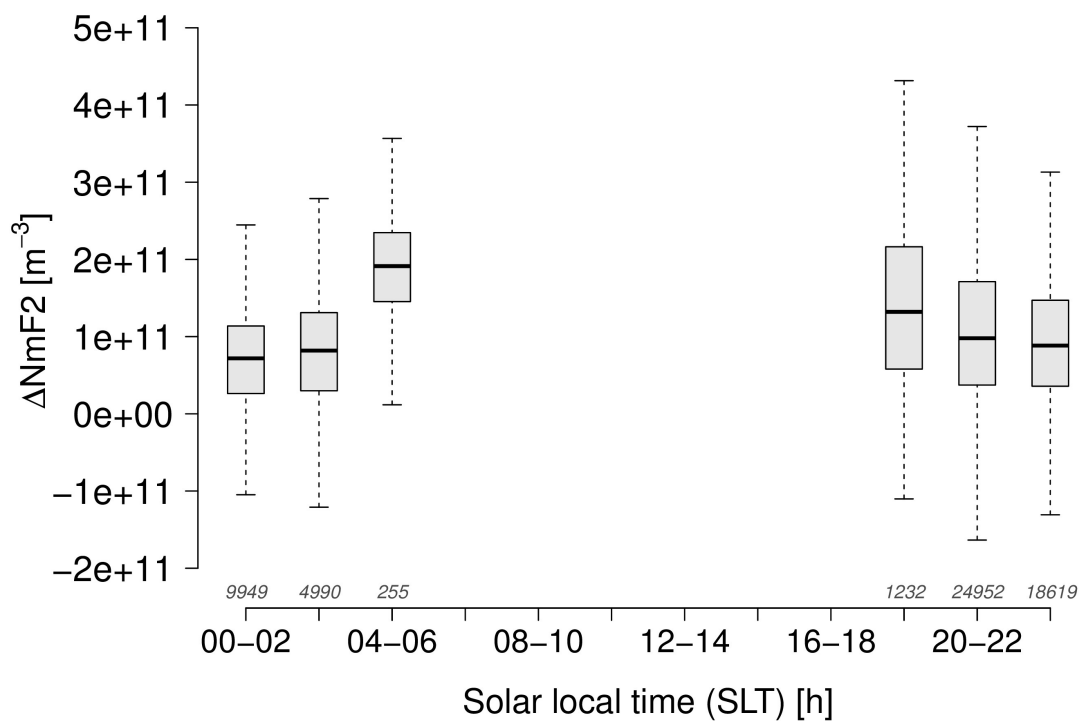


Figure 3b. Same as for Figure 3a but for FUV-C2 comparison.

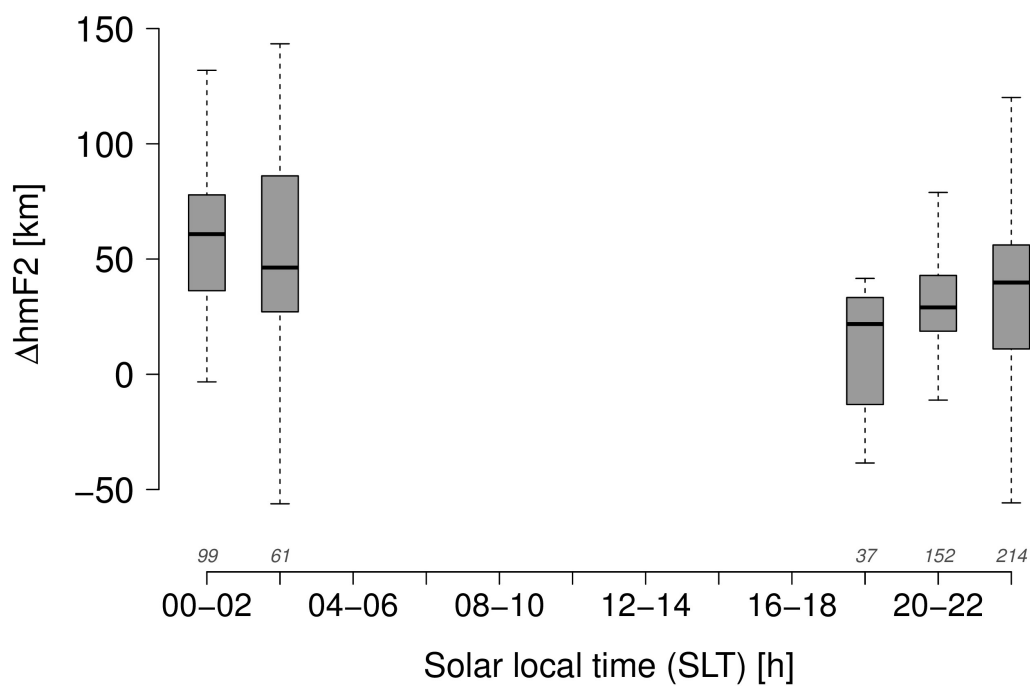


Figure 3c. Same as for Figure 3a but for $\Delta hmF2$.

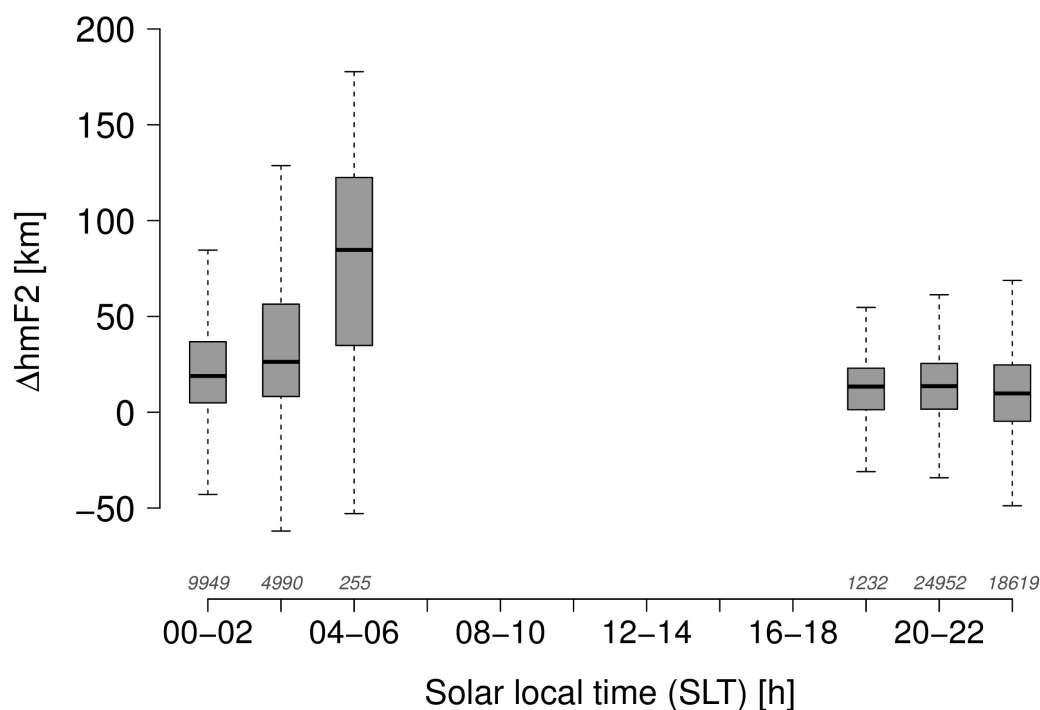


Figure 3d. Same as for Figure 3c but for FUV-C2 comparison.

Analysis

- Solar Local Time has a non negligible influence on the discrepancies between FUV and the other data sources.
- The smallest differences in both NmF2 and hmF2 are observed during the deep night, several hours after sunset (from 22 to 02-04 LT).
- There is a disagreement in Δ NmF2 for the 00-02 LT slice between C2 and ionosonde datasets. It may be due to an isolated case in the ionogram database: ionosonde sample is < 100 while that related to the C2 dataset is 20 times larger.
- The hmF2 differences with respect to C2 seem to converge to the value of about 10-15 km during the very deep night, while mean differences up to 80 km can be observed before sunrise (04-06 LT slice). This effect is not visible in the ionosonde dataset, maybe because of the small number of coincidences for some SLT slices. More generally, hmF2 comparisons with C2 are more reliable due to their very large sample size and the ubiquity of the conjunctions.

RESULTS: EUV

1. COSMIC-2 difference maps

5° x 5° binning of $\Delta N m F2$ and $\Delta h m F2$ and averaging within each bin for EUV-COSMIC-2 comparison.

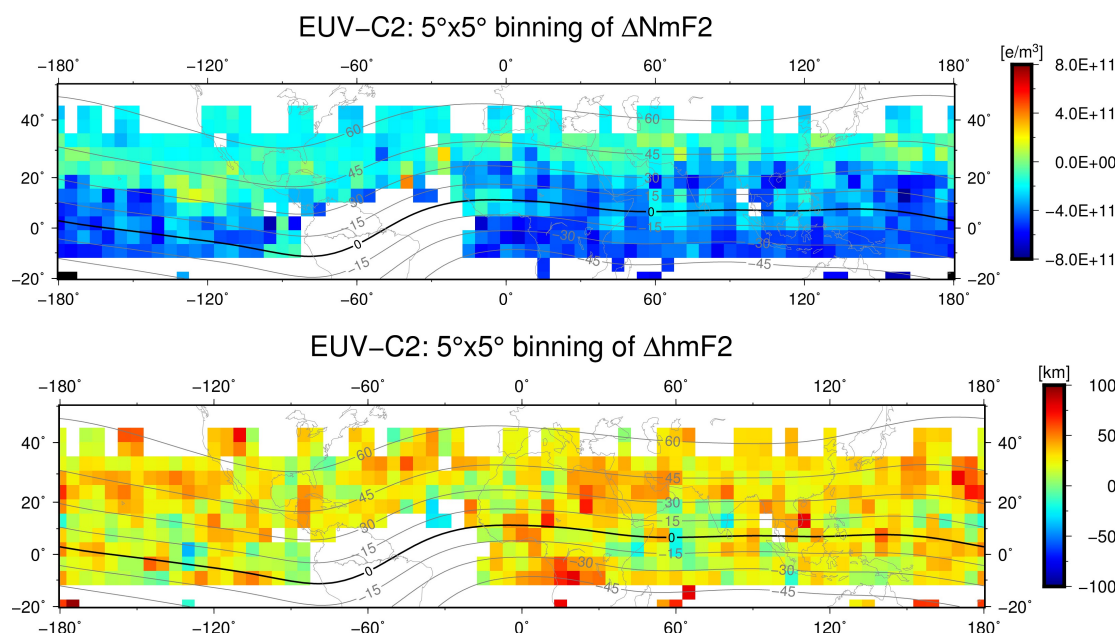


Figure 4. 5°x5° bins of averaged $\Delta N m F2$ (top) and $\Delta h m F2$ (bottom) for C2-EUV comparison. Data gap over South America corresponds to the South Atlantic Anomaly (SAA). Contour lines correspond to geomagnetic inclination, in degrees

Analysis

- $\Delta N m F2$ values are generally negative (blue) at the global scale. However, values close to zero (greenish pixels) and positive values (yellow pixels) are observed above 30° dip inclination in the northern hemisphere.
- There is a cluster of positive $\Delta N m F2$ values (yellow pixels) in the Pacific sector, especially around Hawaii, between 30° and 45° dip inclination
- $\Delta h m F2$ are mostly positive at all longitudes and no obvious latitude or longitude dependence can be deduced from Figure 4.

2. Summary statistics

	N	$\Delta NmF2$ [m^{-3}]	$\Delta NmF2$ [%]	$\Delta hmF2$ [km]	$\Delta hmF2$ [%]
EUV - COSMIC-2	12838	-3.3E+11 +/- 2.6E+11	- 46.2 +/- 31.1	23.7 +/- 33.4	9.5 +/- 12.5
EUV - ionosonde	758	-1.8E+11 +/- 7.6E+10	-51.5 +/- 17.1	17.3 +/- 27.4	8.5 +/- 12.6

Table 2. Mean and standard deviation of $\Delta NmF2$ and $\Delta hmF2$ for EUV-C2 and EUV-ionosonde comparisons

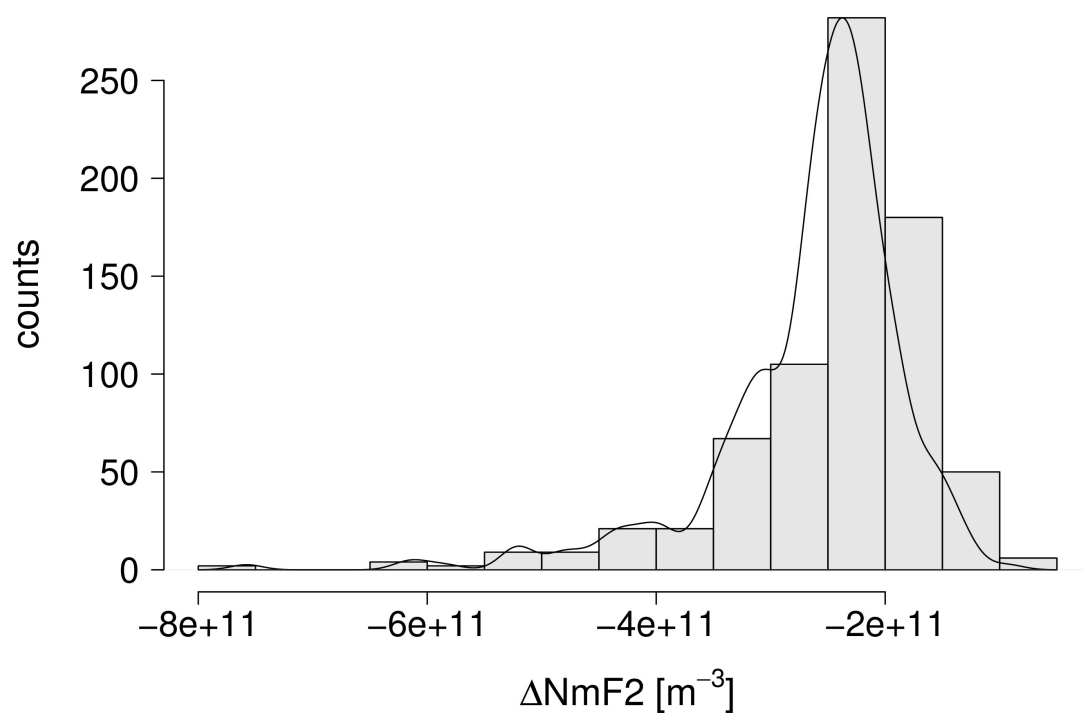


Figure 5a. Histogram of $\Delta NmF2$ for EUV-ionosonde comparison

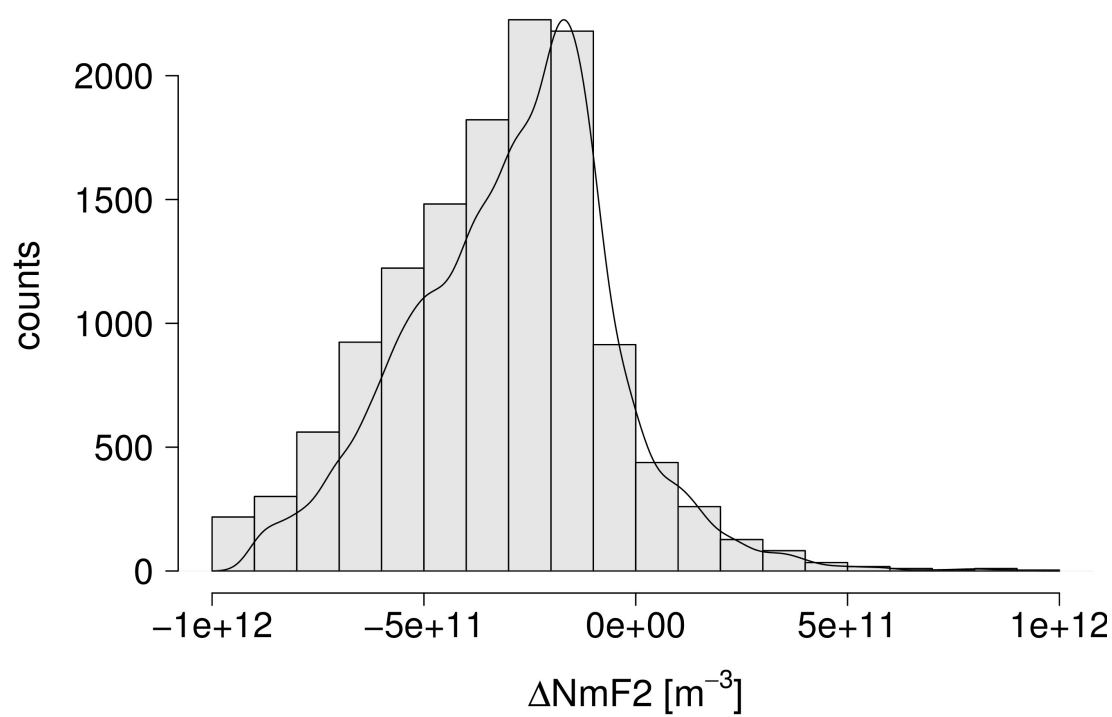


Figure 5b. Histogram of $\Delta NmF2$ for EUV-C2 comparison

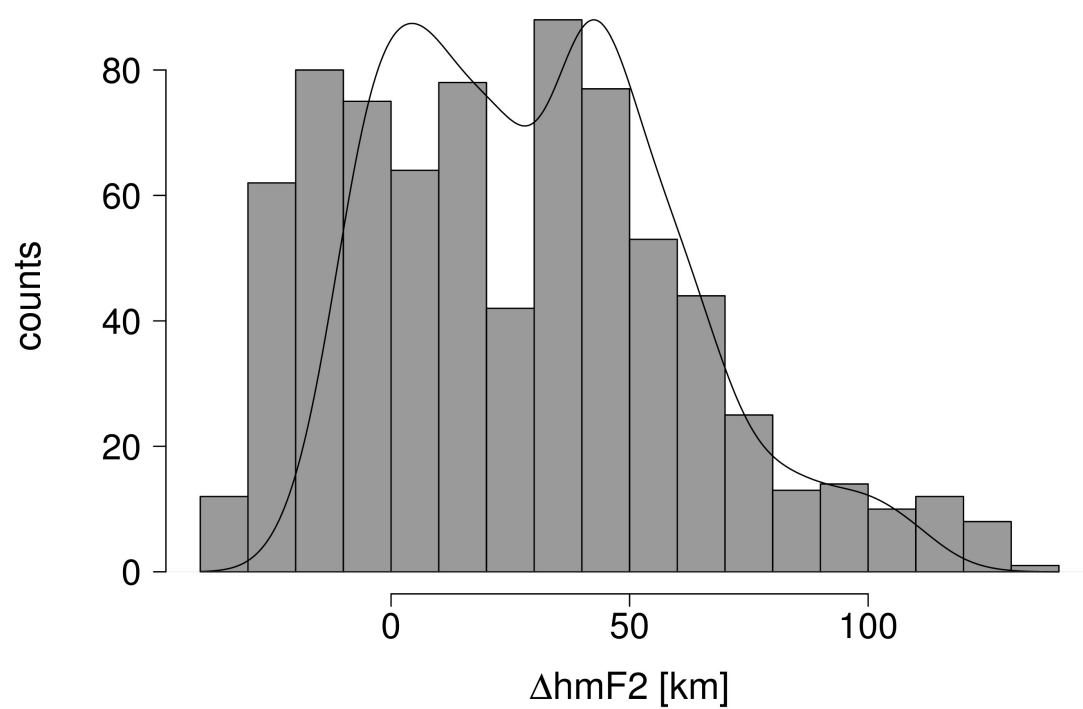


Figure 5c. Histogram of $\Delta hmF2$ for EUV-ionosonde comparison

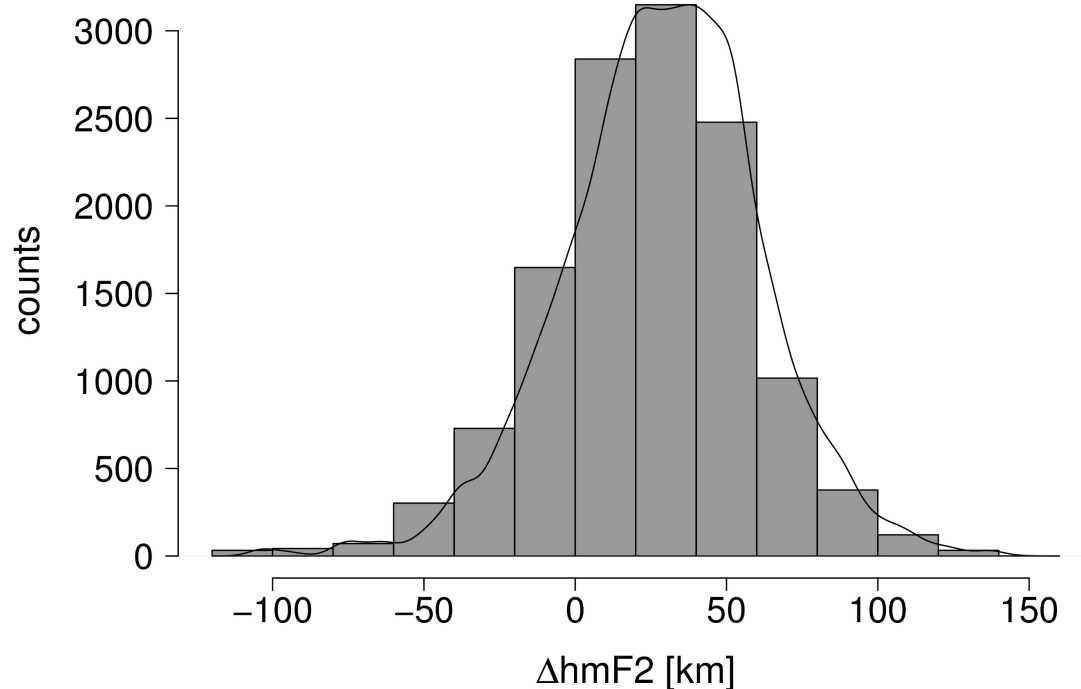


Figure 5d. Histogram of ΔhmF2 for EUV-C2 comparison

Analysis

- Unlike for the FUV analysis, the shape of all histograms cannot be assimilated to a Gaussian curve. We should then be careful while interpreting mean and std. dev. results for these cases, especially when considering ΔhmF2 between EUV and ionosonde (Figure 5c).
- Ionosonde and COSMIC-2 results lead to similar conclusions for NmF2 in terms of relative numbers (about -50% in average), but not in absolute value which varies by a factor of 2. This is explained by the reduced size of the ionosonde dataset, characterized by low NmF2 values in Jan - Feb. 2020. Remind that most of ionosondes are located at mid-latitudes, shifting the average NmF2 towards lower values.
- HmF2 results are also very similar between C2 and ionosonde, with 5 km difference only between the two comparison datasets on average. However, as mentioned above, using a mean value for the ionosonde dataset is not statistically rigorous given the bimodal distribution of Figure 5c. More ionograms are needed to confirm this results.

3. SLT dependence

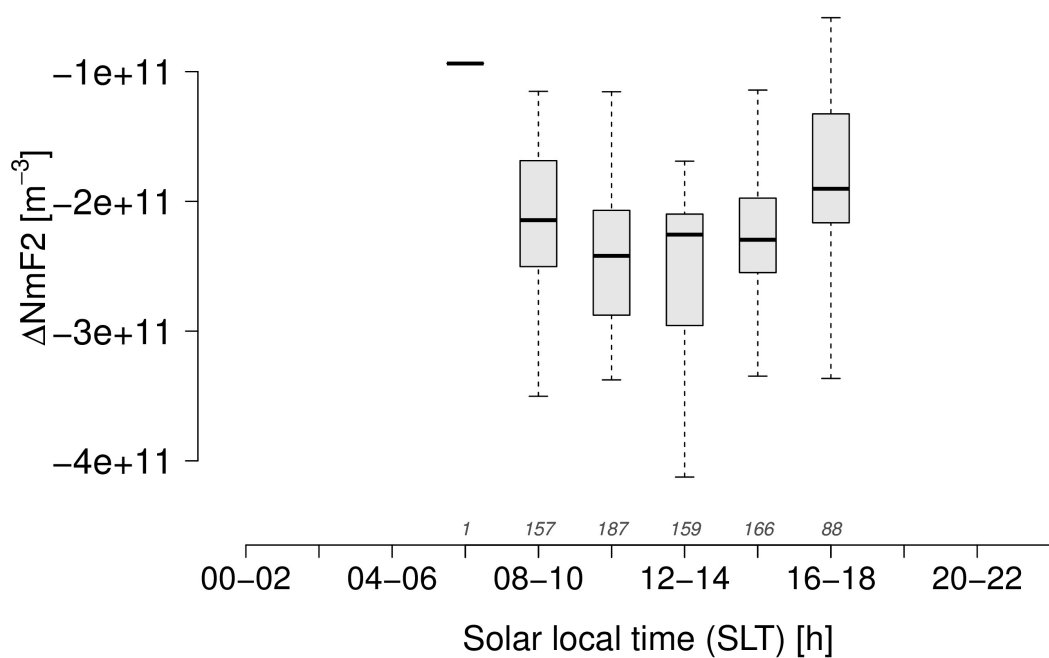


Figure 6a. Boxplots of $\Delta NmF2$ for EUV-ionosonde comparison for six SLT intervals. Boxes represent the quartiles, the median is the thick black line inside the box while the whiskers are located at 1.5 times the interquartile range. The small numbers in italic below the boxplots correspond to the sample size. Outliers are removed from the panel for the sake of clarity.

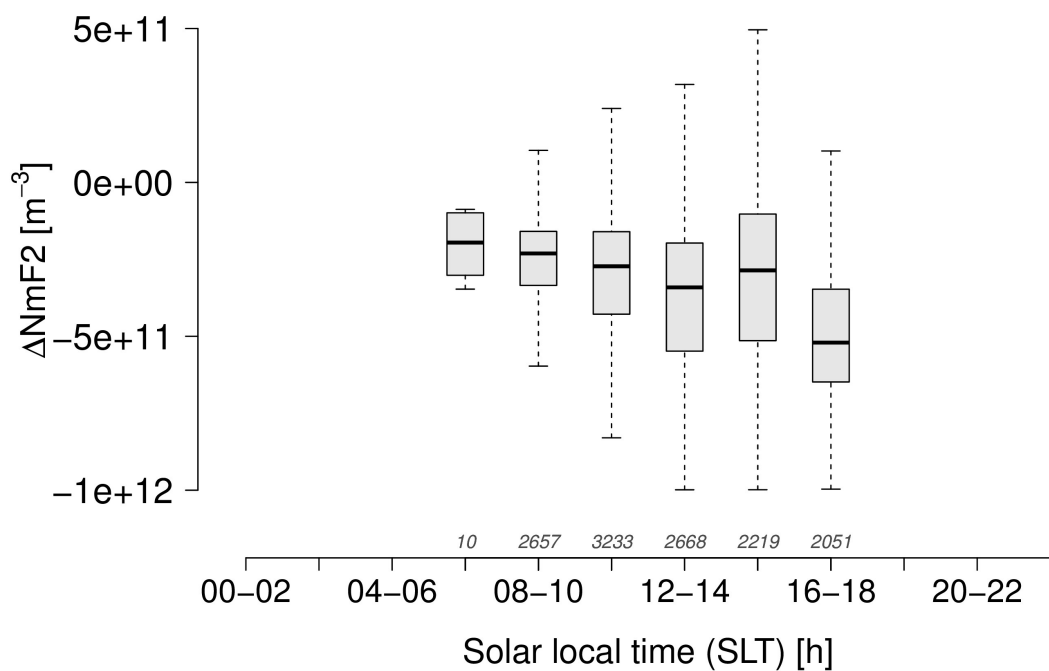


Figure 6b. Same as for Figure 3a but for EUV-C2 comparison.

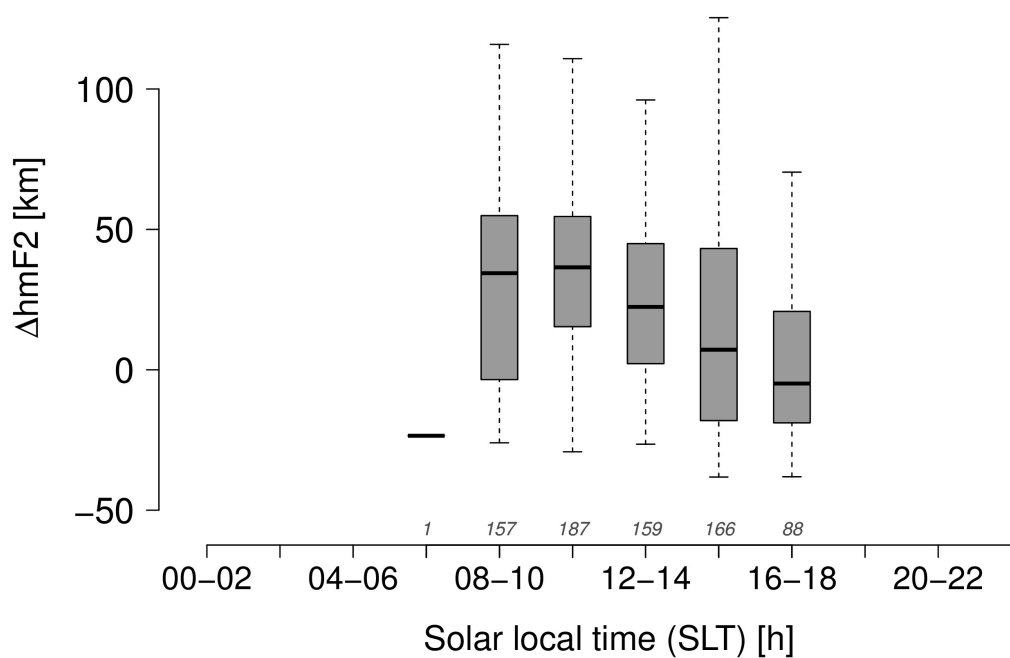


Figure 6c. Same as for Figure 3a but for $\Delta hmF2$.

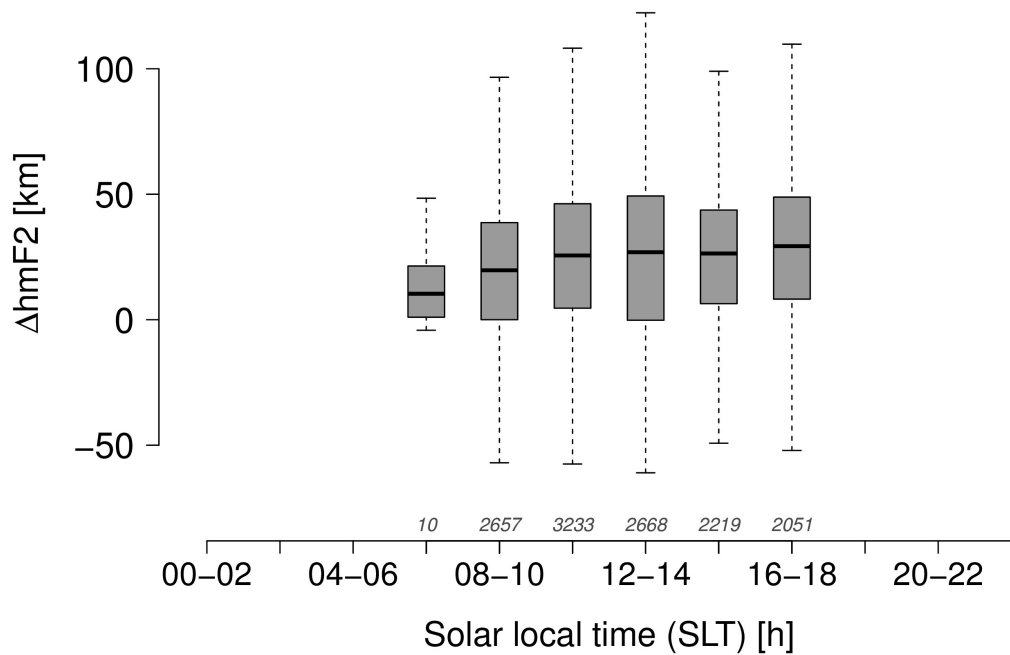


Figure 6d. Same as for Figure 3c but for EUV-C2 comparison.

Analysis

- Like for FUV analysis, Solar Local Time has a non negligible influence on the discrepancies between FUV and the other data sources.

- For the comparison with ionosonde data, $\Delta N m F 2$ is smaller for conjunctions around the morning and evening terminator (Figure 6a).
- For the comparison with the COSMIC-2 dataset, the mean difference decreases with increasing local time (Figure 6b). These observations are not compatible with that related to the ionosonde dataset and it cannot be concluded to a relation between $\Delta N m F 2$ and SLT.
- For the ionosonde dataset, the $h m F 2$ difference is the largest around noon and tends towards zero near the terminator (Figure 6c). The C2 dataset suggests that there is a slight linear trend of $\Delta N m F 2$ with local time (Figure 6d). Like for $N m F 2$, these two contradictory observations prevent drawing an obvious and unique relationship between SLT and $\Delta h m F 2$.

SUMMARY AND FUTURE WORK

DISCUSSION: A GEOMETRIC APPROACH

There is a large variability about the mean and median values as observed in histograms and boxplots.

In the case of line-of-sight integrated observations such as those from C2 and ICON, the observing geometry is of some importance. The regions crossed by both lines of sight should therefore preferably be similar, in order to produce comparable observations, i.e. both lines-of-sight should be as parallel as possible.

→ **geometric filter**: selection of lines of sight for which the azimuth difference between ICON and C2 is $< 30^\circ$

New summary statistics:

	N	$\Delta N m F2$ [m^{-3}]	$\Delta N m F2$ [%]	$\Delta h m F2$ [km]	$\Delta h m F2$ [%]
FUV - COSMIC-2	2067	6.6E+10 +/- 8.0E+10	62.7 +/- 133.1	25.3 +/- 44.9	9.6 +/- 16.9
EUV - COSMIC-2	1439	-3.0E+11 +/- 2.5E+11	-41.7 +/- 28.3	21.4 +/- 33.2	8.8 +/- 12.6

Table 3. New FUV and EUV vs COSMIC-2 summary statistics considering azimuth filtering: $\Delta \text{azimut} < 30^\circ$

Comparison of these results with that of Tables 1 and 2

- FUV: $\Delta N m F2$ sees its mean and std. dev. significantly decrease in absolute value but not in a relative way.
- FUV: $\Delta h m F2$ is significantly larger when considering the azimuth filtering.
- EUV: Despite a slight decrease of the mean values for $\Delta N m F2$, the other parameters are roughly identical
- In conclusion: the azimuth filtering does not seem to significantly decrease the differences between ICON and C2, contrary to our expectations. More work is needed to better understand the causes of such discrepancies.

SUMMARY AND FUTURE WORK

- This work is the first large-scale comparison of ICON FUV and EUV O+ density profiles with external data sources
- COSMIC-2 and ionosonde provide similar trends but absolute and relative values of the differences can differ
- FUV provides slightly larger NmF2 values than external data, the difference being increased during the early morning hours
- FUV hmF2 values are on average moderately higher than for external data, the mean offset ranging between 15 and 25 km on average, but can be larger during morning hours
- EUV NmF2 values is significantly lower than that of external data by around -50% on average. This is less the case for mid-latitude regions where very small differences have been observed
- EUV hmF2 are about 20 km larger than that of external data sources
- In the future, new ionosonde datasets should be investigated, in particular at low-latitudes and in the southern

hemisphere. C2 "ionPrf" final products are also expected; indeed, the present work considers provisional data only

- Being considered as the most accurate technique for ionospheric remote sensing, Incoherent Scatter Radars (ISRs) should also be used as a comparison source.

ABSTRACT

In October 2019, NASA-ICON was launched to observe the low-latitude ionosphere using in-situ and remote sensing instruments, from a LEO circular orbit at about 595 km altitude. The six satellites of the radio-occultation program COSMIC-2 were also successfully launched and currently provide up to 3000 electron density profiles on a daily basis since October 1, 2019. Besides, the network of ground-based ionosondes is constantly growing and allows retrieving very accurate measurements of the electron density profile up to the peak altitude. These three sources of scientific observation of the Earth ionosphere therefore provide a very complementary set of data.

We compare O^+ density profiles provided during nighttime by the ICON-FUV instrument and during daytime by the ICON-EUV instrument against electron density profiles measured by COSMIC-2 and ionosondes. Co-located and simultaneous observations are compared on statistical grounds, and the differences between the several methods are investigated. Particular attention is given to the most important variables, such as the altitude and the density of the F-peak, hmF2 and NmF2. The time interval considered in this study covers the whole ICON data availability period, which started on November 16, 2019. Manual screening and scaling of ionograms is performed to ensure reliable ionosonde data, while COSMIC-2 data are carefully selected using an automatic quality control algorithm.

A particular attention has been brought to the geometry of the observation, because the line-of-sight integration of both airglow and radio-occultation measurements assimilates horizontal and vertical gradients. As a consequence, the local density profiles obtained by inversion of the ICON and COSMIC-2 observation cannot be exactly assimilated to vertical measurements, such as vertical incidence soundings from ionosondes. This slightly limits the reach of the interpretation of the comparison between data of different origin. However, using similar observing geometries, the comparison of ICON and COSMIC-2 data does nevertheless provide very reliable and valuable comparisons.

REFERENCES

Wautelet *et al.*, First ICON O⁺ density profiles comparison to ground and space-based measurements, Journal of Geophysical Research: Space Physics, *in prep*